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Arenas of expectations for hydrogen technologies

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ABSTRACT

Technological development is often described as an evolutionary process of variation, selection and retention. Different technologies are seen as variations, while the market and other institutions operate as a selection environment. It is less understood, however, how variation and selection relate in the case of emerging technologies. In this paper we introduce the concept of arenas of expectations to examine the relationship between variation and selection processes. Expectations are of particular interest in a pre-market phase of innovation, when performance, cost and other market criteria are less articulated and not stable. In arenas of expectations 'enactors' of particular technological variations voice and maintain expectations, while 'selectors' will compare and assess the competing claims. We analyse the expectations work of both parties in a case study on metal hydrides for the on-board storage of hydrogen for automotive applications. The paper concludes with a framework of 'arenas of expectations' as the linchpin between the processes of variation and selection of emerging technologies.

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1. Introduction

It is a truism that technological change proceeds with trial and error. Technological development or innovation is often described as a continuing evolutionary process of variation, selection and retention [1,2]. Different technologies are seen as the variations, while the market, in a broad sense, is their selection environment. Successful innovations are assumed to fit best with their given markets. In the selection environment choices are made between different technological options at the level of individual technologies, and, eventually, at the level of sociotechnical systems [3]. The evolutionary process of variation and selection thus assumes competition between the various emerging technologies. While the evolutionary perspective has proved to be fertile and has led to important further insights and new policy inspiration [3,4] it also raises the problem on *how variation and selection are related*. A strict evolutionary metaphor for technological change must be inappropriate, since variations are not blind and selection is not fully independent. The *quasi*-evolutionary model introduces the role of agency and stresses the connection between variation and selection through anticipation and strategies of various actors [5–7]. Actors anticipate the selection environment because they have some understanding of its future demands, for instance by extrapolating ongoing improvements. Actors will also seek to modify selection environments, by voicing expectations or with other moves like forging strategic alliances. The quasi-evolutionary approach, thus, provides us with a model of technological development and competition that is not dependent on spontaneous, blind variation, but instead relies on guided search through different heuristics and on strategic moves to shape the selection environment. According to the quasi-evolutionary model, variation and selection are interrelated and embedded in a so-called 'cultural matrix of expectations' [5]. This matrix is the set of expectations about the variations and about the selection environment they have to fit. And, the heuristics that guide technological development are embedded in this matrix, according to Rip and van de Belt.

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A further elaboration of the interplay between variation and selection is developed by Garud and Ahlstrom [8]. They argue that a socio-cognitive 'game' is played between, on the one hand, actors that create or 'enact' technological development ('enactors' as suggested by Rip [9]) and, on the other hand, actors that select technologies according to their criteria ('selectors'). Enactors create and put forward technological variations that they claim to be solutions to perceived problems. Selectors, however, start with their (often different) perception of the problem that needs to be solved, and assess how various technologies may contribute to a solution. Note the differences in degrees of freedom between enactors and selectors: the fate of enactors is much more related to the success of one or more technologies, while selectors can afford to be much more indifferent to the fate of a particular technology. According to Garud and Ahlstrom, enactors and selectors meet in so-called 'bridging events' such as funding decisions or technology assessment exercises.

In this paper we aim to develop further the understanding of the role of expectations in the enaction and selection of emerging technologies. Our claim is that the quasi-evolutionary framework does address the role of expectations, but less clearly the question of how expectations are put forward and how they are assessed. This is especially problematic in those cases in which multiple technological options compete for selection. In such cases, the enactors need to position their option in relation to other options, and selectors need to select those options that they deem most viable.

Hence, we propose a next step and argue that variation and selection of future technologies connect through expectations and we introduce the concept of 'arenas of expectations'. The arenas of expectations are then the linchpins between those actors that enact their technological options and those actors that select the most promising options. In the arenas of expectations, claims about future technological options are launched, compared, elaborated and assessed. In the next section we first elaborate on the role of expectations in innovation processes following the relevant strands from the literature, in particular the sociology of expectations and we relate this to the literature on technological communities and R&D evaluation. We present a case study in which the confrontation between variation and selection can be traced for several decades (Sections 3 and 4). It concerns a particular technological variation to store hydrogen in vehicles. Storing large enough quantities of hydrogen on board of vehicles is crucial within the vision of hydrogen as the fuel of the future. Yet hydrogen storage remains rather problematic thus far [10]. The community of researchers working on metal hydrides claims that hydrides might solve the storage problem in the future. In this way they remain visible in the different roadmaps and foresight reports, and secure their position on research agendas and ultimately receive funding for their work. We studied the expectations work of the metal hydride community and the various anticipated and actual confrontations with their competitors and their selectors in arenas of expectations.

The paper concludes with a further reflection on the role of agency and expectations in the co-evolution of technological variations and their selection environment. In the resulting framework of 'arenas of expectations', 'enactors' (i.e. communities that develop technological variations) feed and test the future outlooks of a technology vis-à-vis the concerns and hopes of technology 'selectors'.

2. Expectations and communities

Expectations are of great importance for the development of technologies as they stimulate, steer and coordinate action of actors [11]. The idea of expectations as key element of technological innovation was examined by Van Lente [12,13], and has been developed into a 'sociology of expectations' [11,14]. A working definition of technological expectations, in the context of innovation, is provided by Borup et al. [11]: technological expectations are real-time representations of future technological situations and capabilities. That is, it is a combination of expected progress of the technology at stake, its future markets, and its societal context. Promises and expectations of emerging technologies are part of an agenda setting process [15] and thereby help to create a *mandate* for engineers and other actors [16]. This mandate, in terms of funding and other forms of credit, gives them the opportunity to continue the development of 'their' technology. A mandate, by definition, comes with requirements that should be met; expectations and promises lead to requirements. Steering and coordination of action is done through the voicing of and responding to expectations as well. Coordination can be achieved when expectations are common reference points for actors in different communities or different levels of technology development [11,17].

Expectations inform all parties, but they are not automatically accepted at face value, of course. On both sides, criteria are used to assess variations, both in terms of expected performance (ex-ante) as well as in terms of actual performance (ex-post). These criteria however are not necessarily stable and shared by all actors, as many studies of technology have shown [18,19]. As a consequence, criteria are shaped by actors' needs, vested interests, lobbying and learning processes. There is not one best technological solution to a single problem; for different actors, different technologies fit best. Enactors, for instance, will stress the criteria that will favour their particular variation. Technology selectors, on the other hand, have to balance a number of, sometimes contradicting, criteria and this balance could very well shift over time. The outcomes of processes of quasi-evolution of technology are therefore as much determined by social processes, such as strategic games and the construction of needs and selection criteria, as they are by material characteristics [20].

The role of expectations is most pertinent in the earliest phases of the innovation process. Sometimes, selectors judge technological options on facts, specifications, and actual proofs of the usefulness and economics of variations. In the bicycle case presented by Bijker [19] for instance, artefacts are judged on actual performance and interpretations. Even though different users (end-stage selectors) have different perceptions of what a bicycle is and should do, the bicycle models could be tried and tested in practice.

In the case of emerging technologies and sociotechnical systems, however, investment decisions (and other pre-selections) have to be taken in an early stage of development, when the technologies are not yet prone to such trials of actual performance. In

this situation uncertainty is much higher and actors have to make decisions based on expectations rather than facts [21]. In the case of hydrogen technologies, numerous technological capabilities and societal aspects are indeed very uncertain. In some niche markets, commercial applications are used already, but the first commercially viable hydrogen car has yet to be built. A lot is known about the laboratory performance and specifications, a bit less about prototypes, but far less has been learned about real-life use, system integration, possible learning curves, and economies of scale. Expectations of possible improvements are thus the only basis for decisions to be taken in this phase, for enactors and selectors alike.

As many emerging technologies are highly complex and systemic in nature, it takes a multitude of actors and organizations to develop the actual technologies and make them work. One conceptualization of such groups of actors and organizations is provided in the literature on technological communities [22–25]. The concept of technological (or innovation [26]) communities is used to describe and understand the inter-actor and inter-organizational behaviour in innovation. According to Rappa and Debackere, technological communities can be defined as:

“group of scientists and engineers, who are working towards solving an interrelated set of technological problems and who may be organisationally and geographically dispersed but who nevertheless communicate with each other” [22].

This definition is applicable to the group of scientists and engineers who work on the different component technologies for the hydrogen energy system. They are globally dispersed but have a shared goal to develop solutions and a shared interest in convincing technology selectors of the future potential of their work. Most of this body of literature is concerned with the co-evolution of communities, ‘their’ technologies and their competition with other communities [24]. How these communities use expectations and promises in this competition has received less attention. We argue that expectations work, next to technological success, is important to the growth and success of any technological community.

For a specific technology, there is a technological community working on the concomitant technological options, consisting of researchers in academic science, research institutes and industry. From the literature we take two characteristics of technological communities. The first is the composition of a community. The major distinction is between members from academia and members from industry, given the difference in (community) behaviour displayed by these two groups, which is a relevant distinction because it will have an effect on ‘expectations work’. Scientists tend to maintain positive expectations as long as these provide them with a mandate and with funding to continue their research activities. For industry it seems that meeting expectations is more vital and hence they tend to compare and test expectations.

The second community characteristic derived from the literature deals with the type of binding factor in the community. Academics are in general concerned with a specific field of knowledge (their specialism or ‘paradigm’) whereas industrial actors care about finding solutions that work for the constellations they are interested in. In other words, a dominantly academic community focuses on a specific area that promises to be relevant, in the end, for a wide, and relatively unspecified set of problems. An industry dominated technological community, on the other hand, is bound by the search for means to meet a goal, based on the community’s competencies or other grounds. In the literature this distinction has been characterized as between paradigm-driven versus solution-driven communities, or between design-based versus sponsor-based communities [27].

Furthermore, it is stressed that a technological community is a heterogeneous entity and that actors have different roles within the community. One could expect, for instance, a hierarchical distance between leaders and spokespersons on the one hand, and, on the other hand, scientists and engineers that are mainly concerned with the work floor. A community leader, say, a highly respected professor, is more likely to engage in explicit expectations work than a laboratory analyst. Also, the personal expectations held within the community might differ [28].

3. Chained expectations of hydrogen technologies

In the wider community of hydrogen technology developers, many different technological communities are at work for specific technological options. Together, these communities are in competition with other communities that develop alternative cars of the future, such as electric and biofuel vehicles. At the same time, the hydrogen communities are in competition with each other over the question: who is working on the most promising solution?

As a result, different interpretations of the ‘hydrogen vision’ circulate. And, while car manufacturers claim to be working on the commercialization of hydrogen vehicles and hydrogen demonstration projects are set up worldwide, the future of a ‘hydrogen economy’ is still highly uncertain. In hydrogen vision reports [29–34] a number of similar, yet slightly different visions are explicated [35]. These visions aim at mobilizing support for hydrogen technologies, as hydrogen is not the only contender in the race for the fuel of the future. For mobile applications, hydrogen faces competition from, amongst others, bio fuels and various types of battery electric vehicles [36,37].

Given the large uncertainties about the future of energy production and consumption, the hydrogen visions tend to be rather open and ill-defined in terms of specific technological solutions.

This openness leaves room for interpretation and incites a competition between different specific proposed solutions for the various challenges. As a result, enactors are faced with a fundamental ambiguity: hydrogen proponents, on the one hand, compete with other hydrogen technologies; on the other hand, they need to downplay the competition to convince outsiders of the future possibilities of hydrogen in general. They can claim or colonize [14] their share in the future of transportation energy systems and use all kinds of arguments to support hydrogen and to build on a number of positive images of hydrogen technologies [38]. To make the hydrogen vision(s) credible, proponents and other interested actors need to show the technological possibilities of the

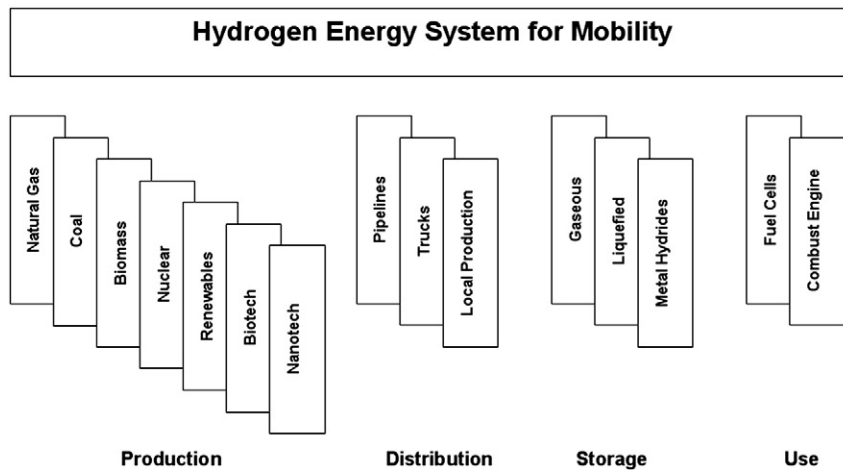


Fig. 1. The prospective chain of hydrogen energy technologies. It contains the four main elements (production, distribution, storage and use) for which a number of 'promising' options are put forward.

hydrogen energy system in its entirety. Commonly, the envisioned hydrogen energy system is divided into four main elements: production, distribution, storage and end-use. For each of these four elements a number of enabling technologies and approaches are proposed as viable candidates. Hydrogen technologies are thus arranged in a nested hierarchy of system, subsystem and component technologies [39].

Currently, none of these technologies, subsystems or systems is 'ready' for implementation without further development, testing or adaptation. At least for vehicular use, they are either too expensive, not efficient enough or have not proven to work at all.¹ The configuration of elements of the hydrogen vision is what we define as the *prospective chain* of hydrogen technologies. It is not in existence yet, but it is a projection of things that could come into being and hence it is fundamentally prospective. In all hydrogen visions the prospective chain, or variants of it, is filled in with interdependent promising technologies. Fig. 1 depicts the prospective chain with the most common 'promising' technological options for each of the elements [40]. The options range from rather short-term ('almost ready') options such as hydrogen production from natural gas, to truly long-term and highly uncertain options such as hydrogen production with the help of nanotech solar panels or genetically modified algae.

Despite the fact that none of these technologies is truly satisfying and commercially available, hydrogen visions have to build upon them for their credibility. This implies that hydrogen visionaries and other proponents necessarily create and maintain expectations about component technologies as well as about a hydrogen energy system or even a 'hydrogen economy'. The chain of technologies is thus repeated as a chain of interdependent expectations. Note the double bind: the viability of the hydrogen vision is dependent upon expectations of individual components and the redundancy that is provided by the multitude of options per element, while the credibility of singular hydrogen technologies is derived from their contribution to the hydrogen vision at large.

4. Expectations work for metal hydrides

To study the dynamics of variation and selection on the basis of expectations in more detail, we have performed a case study on one of the hydrogen technological communities, which proposes to store hydrogen in the atomic lattices of metal alloys, forming metal hydrides. This community pursues the storage of larger quantities of hydrogen on board of a vehicle, thereby enlarging the cars driving range. So far however, metal hydride researchers have not found what they are looking for. Still, they can continue their work as long as their sponsors accept the promises and expectations of their quest for better alloys and catalysts.

Our case study builds on a literature study as well as a series of interviews with metal hydride researchers. The first part of the case study aims at identifying the position of metal hydrides in the hydrogen vision. From there on we reconstruct the history of the metal hydrides at the level of the technological community and its expectations work in enacting metal hydrides as a promising option as compared to its competitors. In a next section we zoom in on the individual researchers and their anticipations of the selection process. Finally we conclude the case study with a description of the technology selectors and their assessments of the promise of metal hydrides.

4.1. Metal hydrides and the hydrogen vision

Results of foresight activities on the future hydrogen energy system can be found in many loci; in governmental reports, scientific journals, in engineering circles as well as in popular press. A favoured way to plot the future of hydrogen is to use

¹ Hydrogen is already produced at large scale in the petrochemical industry by means of reforming natural gas. For use as car fuel this process is still too expensive to compete with gasoline in today's market.

technology roadmaps [41] and other outcomes of foresight activities [42]. We have selected six [29–34] hydrogen vision reports and technological roadmaps from different geographical regions and stakeholder groups to position metal hydrides within the hydrogen vision. While these reports sketch the background to our case study, they also expose some of the assessments, of metal hydride expectations, made by technology selectors. We discuss these assessments at the end of this section, but for now the focus is on the position and expectations work of the enactors.

Typically, the reports mention three basic options for on-board storage that are in competition with each other and therefore are relevant to our case study: liquid storage (LH), gaseous storage (GH) and storage in various metal alloys, typically named metal hydrides (MH). Other proposed solutions are much less mentioned, such as storage in nanoparticles (nanotubes) or storage of hydrogen atoms bonded in liquid substances (to be added and removed through chemical reactions). The visions and roadmaps seem to agree on what to expect from the three main solutions of hydrogen storage. All solutions have their own (fundamental) pros and cons and these are figured repeatedly in the reports and other literature. The vision reports can be taken as a representation of the trials of strength between the different enacting communities and their selectors. Based on those reports, we draw a number of conclusions in relation to hydrogen storage options.

First of all, the on-board storage of hydrogen is presented as one of the biggest challenges for the use of hydrogen as energy carrier for mobility. Liquid hydrogen scores very well in terms of volume and weight, but is inefficient in terms of energy: 30% of the energy is lost due to the low critical temperature of liquid hydrogen [29]. Gaseous hydrogen leads to better energy efficiency and is used in practically all hydrogen prototype vehicles (with the exception of BMW's liquid storage²). The gas is pressurized up to 700 bar, resulting in acceptable volumetric densities, but this process consumes about 20% of the energy. Safety concerns and production costs, however, add to the doubts about this solution. In terms of expectations voiced in the documents, liquid and pressurized storage are not seen as very promising. The drawbacks are seen to be caused by thermodynamic laws: pressurizing gas takes energy, and liquefying even more. Although some researchers from these communities work on ways to regenerate the energy, there does not seem to be a lot of room for improvement. Research on gaseous and liquid tank designs focuses mainly on cost reductions and safety improvements. Metal hydrides are, in contrast, less understood and this seems to be their main source of promises; there is a lot to learn and therefore a great potential for improvement. The documents all mention the underdeveloped stage of metal hydrides and at the same time also stress their future potential as compact and energy efficient method for storing large quantities of hydrogen. In other words: metal hydrides might be the 'Holy Grail' of hydrogen storage but the right alloy has not yet been discovered.

4.2. *The metal hydrides community*

The metal hydrides community has actively engaged in expectations work towards its selectors in order to gain and maintain a position on the research agendas. As said, we have performed both a concise literature study and a series of interviews to reconstruct their work towards that goal. The literature study included four review articles on metal hydrides research [43–46]. The semi-structured interviews were held with eight senior metal hydride researchers in the Netherlands. All of them participate in the so-called 'Sustainable Hydrogen' research program which is financed by the Netherlands Organisation for Scientific Research (NWO). About half of the projects financed by this program, originally set up to finance research in chemistry, deals with metal hydride research. The interviewees' research varies from experimental work on new material compositions, to new production methods and computational modelling of the hydration processes and thereby it covers the main subfields of metal hydrides research as found in the review articles.

During the interviews we discussed their activities in communicating expectations to their peers and technology selectors in the different arenas and this helped us to analyse the mandating and constraining process. The interviews also allowed us to reconstruct their framing of the competition between the different storage solutions and to analyse their views on (and anticipation of) the selection criteria used by technology selectors. The interviews were complemented by participatory research during related conferences in the Netherlands.

The first interest in metals as hydrogen storage materials dates back to the 1960s. Researchers shifted their attention from electricity storage in metals (i.e. batteries) to storage of pure hydrogen. Nowadays this community is much larger and consists of researchers from different backgrounds such as chemistry and physics (both experimental and computational). Since 1999 the community has grown rapidly in the EU member states. For instance, in 2003 there were three ongoing EU research programs, whereas in 2008 five networks existed [40]. The number of institutes involved in this research has increased as well. At the time of this case study six research groups were involved in metal hydride research in the Netherlands which equals to roughly thirty researchers. These are located at the universities of Amsterdam, Leiden, Utrecht, Eindhoven, Delft, Twente and Nijmegen. All these institutes take part in the 'Sustainable Hydrogen' research program which is funded by the Dutch research council NWO. The program was an important factor in the growth of the Dutch branch of the hydrides community. Before the start of this program the community was limited to only two university groups. The other groups were dealing with comparable subjects and techniques, but never applied this to metal hydrides for hydrogen storage. During the formation of the research program, one of the communities' spokespersons was invited to suggest a number of research groups that could contribute to the goals set by the Dutch research council. Thereby he was given the chance to widen the community with research groups that did similar work, but

² By means of an internet search we found 3 metal hydride prototypes built by major car companies (Daimler-Benz in the 1980's and Toyota in 1996 and 2001), on a total of about 250 hydrogen cars. With the exception of BMW all manufactures use gaseous storage with pressures of either 300 or 700 bar.

never studied hydrogen storage materials. Since then, the community in the Netherlands has grown in terms of research groups, the number of scientists involved and the scope of research.

4.3. Early years

Since the start in the 1960s, researchers and car manufacturers have shown interest in metal hydrides as means of hydrogen storage and a number of different materials and approaches have been explored. The first hydrides under study were the so-called low-temperature hydrides. These relatively simple hydrides form when hydrogen atoms nestle interstitially in the metal's atomic lattice. The metals used for these hydrides were, amongst others, titanium, chromium and manganese [43]. These hydrides can be used at low temperatures and are thus interesting for on-board applications as no temperature control system is necessary. Their main drawback is the weight of the base metals which results in a very heavy tank system. The weight of the tank system is detrimental to the performance of the vehicle and it is therefore the hydrogen-to-weight ratio of the system that has dominated the metal hydrides research heuristic: gravimetric density. It is often expressed as the weight percentage of hydrogen in the total weight of the system. For the low-temperature hydrides 2 wt.% proved to be the maximum.

The next step came with the high-temperature, but relatively lightweight, metal hydrides. These metals, often magnesium alloys, have poor thermodynamics, but score excellent on gravimetric density. Theoretically these hydrides can contain up to 7.6 wt.% of hydrogen. Unfortunately, these materials can only store hydrogen at temperatures above 200 °C [45]. And this is not suitable for practical use because this would require active heating of the tank system and this lowers the overall energy efficiency of the storage system dramatically.

4.4. New hope

A new impulse to the community was generated in 1997 by Schwickardi & Bogdanovic through their article that demonstrated the high storage potential of aluminates (for instance NaAlH_4) when they are doped with TiO_2 [47]. The titanium oxide catalyst is able to lower the temperature range for ab- and desorption of hydrogen significantly. Their finding spurred new hope for metal hydrides. Research activities intensified significantly as can be seen from the number of articles in *International Journal of Hydrogen Energy* and the *Journal of Alloys and Compounds* [40], two of the main outlets for the community. Together with the burst in aluminates research, a large number of old as well as new hydrides were (once again) given a chance.

The three main characteristics by which the potential of metal hydrides is measured are the aforementioned gravimetric density, the operating temperature range and the kinetics of ab- and desorption. The rate of hydrogen absorption is seen as important because this determines the speed at which a consumer would be able to fill his car at the gas station. Therefore, a lot of effort was, and is, put into processing smaller particles of the most promising alloys. Small particles are desired because the rate of absorption is mainly determined by the length of the path the average hydrogen atom has to travel through its storage medium and also because smaller particles have a bigger surface area to weight ratio. Ball milling of the metals promises to produce ever smaller particles. The same goes for attempts to grow nanosized particles from watery solutions and so-called spark discharge formation. Other recent developments are the so-called MOFs, amides, imides and borohydrides.

Yet, so far no material has reached, under practical conditions, a higher gravimetric density than 3–4 wt.%. This is considered to be too low. The US Department of Energy (DOE), for instance, has set a number of goals for hydrogen storage technology for the coming years. The weight percentage for 2010 should reach 6 wt.% and the 2015 goal is 9 wt.% [48,49]. The goal for 2007 (4.5 wt.%) was not reached. As said, no hydride material has been developed that scores well on gravimetric density, thermodynamics, and absorption kinetics. Likewise, the International Energy Agency and EU have set a number of goals for hydrogen storage systems [50] but these are hardly ever mentioned as reference by the metal hydrides community.

To conclude this short history, metal hydrides have been on research agendas for forty years and expectations of further progress gave researchers their needed mandate. Even more so, the burst of research trajectories testifies to the unshaken belief in the future potential for metal hydrides. We conclude that it must have been expectations that convinced their sponsors because there are hardly any practical applications for metal hydrides yet. An exception should be made for some hydrides that are used for stationary purposes or in some niche markets like submarines [51]. Still, the real promise of low-volume, energy efficient on-board storage has not come true so far.

4.5. Anticipating selection

This short history of metal hydride research shows how the research community managed to survive by feeding and maintaining expectations. The expectations work of the community relates to their own technological option as well as to the competing options. For both, the community anticipates its future selection environment. It has an understanding of what its selectors desire and thus what its message should be. A key argument that the community has brought to the fore during the last decades is that both gaseous and liquid hydrogen storages are not, and will never be, satisfying solutions for the automotive industry. Thermodynamic laws, according to the prevailing arguments, prevent further development of these options in terms of storage capacity and energy efficiency. The metal hydride community continuously points to these limitations and presents their option as the promising, but also challenging, alternative.

The promise of metal hydrides is constructed through a number of arguments. First and foremost, the progress that has been achieved is stressed. That is, even though metal hydrides do not meet most of the targets, some progress was made in terms of

storage capacity and kinetics and an extrapolation of this progress is sometimes used by the community spokesperson to point out what further progress may lie ahead. Second, a better understanding of the underlying chemical and physical processes is seen as starting point for upgrading the materials' thermodynamics and kinetics. This goes especially for the group of aluminates that is under study. And third, it is argued that new alloys and catalysts, with higher capacities and faster kinetics, might be discovered as well.

The community stresses these points in their scientific publications, their contributions to conferences, and their negotiations with research councils. An often cited version of this argument is found in the Schlapbach and Züttel article in *Nature* [52]. Note, however, that the actual feeding of these grand expectations is done by a small number of formal and informal leaders in the community. Discussions like these, about the feasibility of metal hydrides as an alternative to liquid and gaseous storage, take place mostly at conferences and meetings where the wider hydrogen community is present. Only a few spokespersons are structurally involved in these debates.

Other members of the community are more likely to confine themselves to small scale expectations work in their research proposals and papers. These expectations relate to the outcomes of small research steps, rather than the wider potential of metal hydrides. According to the researchers, the claims are mostly qualitatively formulated such as: 'through better understanding of the underlying reaction mechanisms, we will be able to enhance the materials properties'. The claims made in research proposals are almost never quantitative. One reason for this is that the scientists prefer to be prudent in their predictions in order to avoid disappointments on the selecting side:

"You will state in general terms that you want to destabilize the hydrides. Thereby you do not specify exactly what destabilizing is, that it occurs at eighty degrees or some specific pressure." (senior metal hydride researcher)

The interviewees are not sure, however, how and when this disappointment could affect their mandate for further work. The focus of their expectations work concerns their specific research plans, while the promise of metal hydrides as such is not explicitly voiced but implicitly assumed. When they are asked to voice the expectations of their community they do this with the same modesty. Again, they do this to avoid disappointment and because they feel that many other actors are capable of judging the progress and potential of metal hydrides as well:

"You should have some ambitions, but you should not exaggerate. In a few years you will be held accountable and then you lose more than what you started with." (senior metal hydride researcher)

The small scale expectations work relates mostly to specific hydrides, catalysts, production methods, simulations, etc. Here the importance and potential of metal hydrides is taken for granted; what matters is that specific research is seen as promising within the field. Statements about the necessity of metal hydride research, its promises, its competitors and the bigger issues such as the end of the fossil fuel era and the climate problem, clearly provide societal relevance for the research, but are less useful to promote the option of metal hydrides as such.

4.6. *Selecting technologies*

The promises and expectations that were voiced by the metal hydride community are assessed and used by selecting actors. The selectors are more distributed than the enacting community. As metal hydrides for hydrogen storage are in the science stage of development, research councils and scientific program committees are the most prominent selectors. With support of their respective governments, they select promising research trajectories and the accompanying proposals. They do this by determining promising fields of research, by setting goals and targets, and by assessing results. Next to the research councils, car manufacturers also act as technology selectors; they select or reject technologies for further R&D work and eventually for use in their prototypes and future products.

Note that the distinction between enactors and selectors is analytically clear, but ontologically not straightforward, as actors that are selectors at one moment could act as enactors at another moment. For example, in the case of research councils it is hard to distinguish between enactors and selectors. Research councils are partly made up of scientists and those scientists are often part of the same community they have to select. The same goes for R&D efforts in the industry: the company that enacts the technological solutions is selecting them as well; a firm that decides to use metal hydrides in its hydrogen prototype vehicles, will from there on claim that metal hydrides are a viable option that can deliver the desired performance to its future customers; it is then enacting metal hydrides towards the selectors of their promising options.

Enacting and selecting should therefore be seen as roles that actors play at a given moment. Yet, the distinction between the two sides of the quasi-evolutionary game is important analytically, to study and understand the processes that take place in the variation and selection of technologies. So we argue that it is possible to distinguish a number of selectors in relation to the technological options that are offered.

The selectors of hydrogen technologies and their assessments of the promises and expectations are most visible in the roadmaps and vision documents. Through these documents, the results of negotiations between governments, experts, and firms are communicated to the outside world, and a sketch is provided of the research that is thought to be necessary. To figure in these reports is thus vital to stay on research agendas and receive funding. The argument of the hydrides community, for example that

gaseous and liquid hydrogen are fundamentally limited, is found in these documents as well. In fact, this negative argument seems more prominent than the positive argument in favour of metal hydrides and their future potential.

Since the Bogdanovic article in 1997, the selectors have granted the metal hydrides a wide mandate for further work. Members of the community have had no problems with getting funding for their research. The researchers enjoyed a great freedom in choosing their specific research aims and methods. This implies that the granted mandate, at least within the ACTS program, is quite open. Whether this will last is rather disputed amongst the interviewees. Some believe that the peak of attention has passed and that, especially in the US, budgets will decline. Other interviewees feel that 'things have only just started' and that funding will continue for the foreseeable future.

In the US, governmental research funding has risen over the last years and an even bigger share of hydrogen technologies R&D funding is requested by the DOE for (solid) materials for hydrogen storage [53]. In the EU the picture is a bit different. Research funding for hydrogen storage solutions is continued in academic circles. However, it receives hardly any attention in the application (and demonstration) oriented Hydrogen Joint Technology Initiative (JTI) proposal for the period 2008 to 2015. In this public-private partnership the focus is on production, distribution and conversion (fuel cells) of hydrogen.

There are some signs that expectations of metal hydrides on the part of the selectors are indeed diminishing. This could very well be the result of disappointments about unfulfilled promises of further progress. One example of such disappointment can be found in an assessment report on EU funded hydrogen and fuel cells research. The report critically reviewed the progress of solid hydrogen storage (including metal hydrides) and concluded that the performance is still far from the aspired targets [54]. Both the EU and the US have defined targets for future on-board systems in consultation with the car industry to deliver the same performance, in terms of speed and range, as today's cars. The performance and progress of the different storage options are assessed against these targets and the options are expected to meet different targets at different points in time. In practice, it is likely that none of the known storage systems will meet these targets and therefore the metal hydrides community compares itself with today's leading option, 700 bar high-pressure gaseous storage. The interviewed researchers acknowledge that metal hydrides at this stage cannot meet the performance of the high-pressure tanks, and they are also hesitant about the targets set by the DOE, EU and IEA. While they sometimes use these targets to stress the need for further research, they do not agree with them in terms of the actual needs of the car industry. From their contacts with the industry they figure that a weight percentage of 5% would be enough, provided the system meets other conditions in terms of operating temperatures and fuelling times. Especially the DOE norms are considered to be not realistic and driven by current car design and performance (i.e. SUV's) rather than accepting a different mode of personal transport that would require less hydrogen on board for an acceptable driving range.

5. Conclusions: arenas of expectations

In our case study we have witnessed what types of expectations the metal hydrides community has constructed and how they conveyed these to its selectors. This enacting community has put to the fore why metal hydrides are promising, and why the competing solutions are not promising. We have also witnessed how the selectors responded to these expectations and what mandate was given to the hydride community to continue its research. In this section we place our findings in a generalized framework for the role of expectations in the variation and selection of emerging technologies: *arenas of expectations*.

As outlined in the *Introduction*, technological communities of enactors and their expectations are in competition with each other for funding and other forms of support. They fight their battles on battlegrounds we propose to call arenas of expectations. These arenas can be defined as the loci where expectations are voiced by the enactors and tested by the selectors, where they are confronted with experience, knowledge, and interests. The important point is that ongoing processes of variation and selection of emerging technologies are not just bilateral interactions but a collective social process over time, engaging a lot of different, competing, actors and organizations. These multi-actor interactions take place at scientific conferences and journals, in the wider media, committees, research councils, and so forth. Within arenas of expectations 'trials of strength' [55] take place between the circulating expectations of the different options. An important part of these trials is based on earlier experiences, for instance in the case of failed promises such as we have witnessed in our case study. The expectations are confronted with facts and forces of the social and economical context in which they are supposed to become realities. Therefore, the accumulation of knowledge and failures, expectations and disappointments, hopes and fears become relevant in arenas. It is in the arenas that the cultural matrix of expectations, as proposed in the quasi-evolutionary model of technology development, is given further shape and content. In Fig. 2 we summarize how, in the arenas, the expectations work of the enactors and selectors meets.

It shows, on the left side, that enactors feed and maintain expectations in the arena. They have to do this in order to receive a mandate for further work on improving their technology. This mandate is granted when technology selectors are convinced of the future potential of the technology, that is, for the time being. At stake, thus, is the robustness of the expectations in the arenas; too much contestation harms the mandate for the enacting community. The drawback of robust expectations, however, is that they may constrain the enactor community not to deviate from their promising approach.

Selectors inform (and also constrain) themselves with expectations, they make assessments and pick their winners. As a result, some variations are favoured or at least not too strongly contested by selectors; others are seen as not viable, or as not yet viable. The outcomes of the selectors' decision making process feed back into the arenas and influence the ongoing struggle for mandate. How and why exactly the selectors come to their assessments of the different expectations in the arenas is a question that we think deserves further study. The multitude of options for each of the elements in the prospective chain of hydrogen technologies is testament to the fact that technology selectors maintain a portfolio of options that are given a chance to develop further. Such portfolio approaches are common, but it is not fully understood why some options are thought to be credible and others are not.

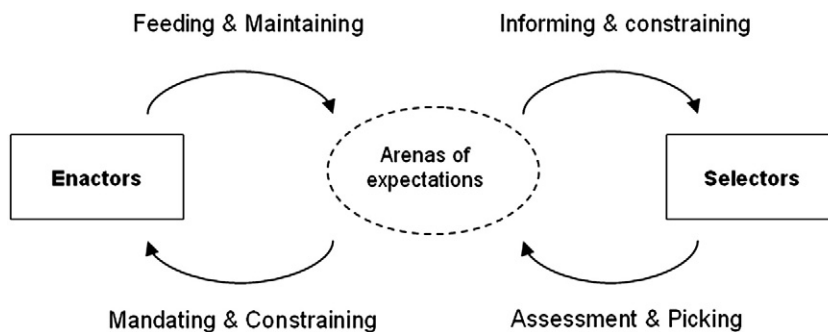


Fig. 2. Arenas of expectations.

From the case study we conclude that multiple arenas may co-exist at various levels of aggregation. Highly detailed expectations of materials or techniques are tested in different arenas than, say, expectations about the hydrogen energy system as a whole. Specific expectations will circulate in specialized scientific committees, where the merits of the 'hydrogen economy' figure in public debates on sustainable energy. Nonetheless, high expectations of a specific hydride alloy may find their way into the vision level arena as well. Be it that in the latter arena it is mostly the community spokespersons that have their say.

In order to study the enaction and selection process in the case of hydrogen storage technologies, we analysed the expectations work, the act of feeding and maintaining expectations, performed by the technological community that tries to develop metal hydrides for hydrogen storage.

In Fig. 3 we have summarized expectations and statements that appear in the hydrogen storage arena of expectations. The short statements in the figure highlight the success of the metal hydrides community in convincing the selectors of their solution's potential for the hydrogen chain of technologies. It has granted them a place in the hydrogen chain and on research agendas, notwithstanding doubts about the cyclability and cost (the search is mostly about finding a lightweight, high capacity hydride).

Expectations about the other storage methods are clearly negative within the metal hydride community: they will not improve significantly and are unfit to support a sustainable hydrogen energy system. Within the wider hydrogen community, a lot of actors, certainly in the car industry, are working on further improvement of gaseous storage and the boundaries are pushed beyond 700 bar. The energy losses involved are apparently acceptable in this phase and it seems that car manufacturers might accept lower specifications than the goals set by the DOE.

Surely, metal hydride researchers support hydrogen as energy carrier and quite often mention the need for a replacement of fossil fuels because of the climate issue and the depletion of supplies. For them, the role of metal hydrides is crucial, while this does not seem the case for actors in the wider hydrogen arena. The wider hydrogen community, including its selectors, regards on-board storage as highly important, but the development of metal hydrides is not vital to the future of hydrogen. Still, metal hydrides provide a useful promise to silence the critics of hydrogen as fuel of the future. That is, the very fact that there is an option for on-board storage that holds the promise of solving the storage problem in the future, makes the prospective chain of hydrogen technologies a bit more credible.

To conclude, the exchange or communication of expectations does not only take place in bilateral and synchronous fashion during bridging events as proposed by Garud and Ahlstrom [18], but also in a more multilateral and asynchronous fashion through scientific articles, foresight activities, roadmaps, funding decisions, etc. The actors and their expectations and promises meet in different arenas of expectations for different aspects of the technology and for different levels within the prospective technological system. The interaction between enactors and selectors in the arenas of expectations results in the coordination of research

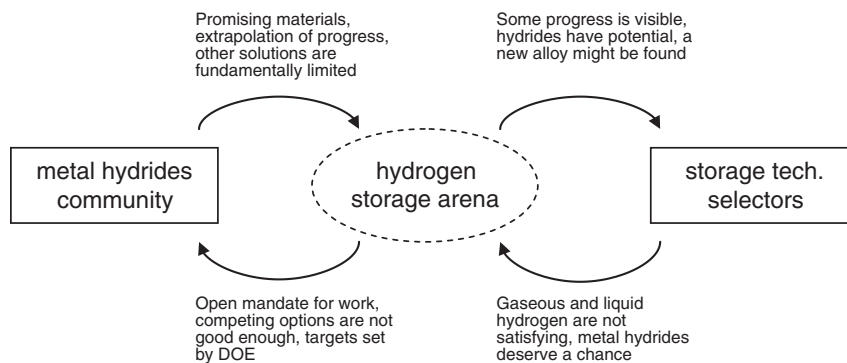


Fig. 3. The expectations work in the hydrogen storage arena.

activities, the selection of technologies and their further development for market introduction. Arenas of expectations, therefore, provide an important link between the processes of variation and selection.

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